B Physics at the Tevatron

Jack Cranshaw[a] *for the CDF and D0 Collaborations*

[a]Texas Tech University, Lubbock, Texas 79409

A vibrant B physics program is being pursued at the Tevatron for Run II using the upgraded accelerator complex and the upgraded CDF and D0 detectors with the goal of collecting 2 fb^{-1} of integrated luminosity. This will provide measurements of various CP parameters which both complement and extend the programs at the B factories. There are also a variety of spectroscopy measurements currently available only at the Tevatron. The detectors are now largely commissioned and data acquisition is underway.

1. Introduction

The Tevatron is a $p\bar{p}$ collider at the Fermi National Accelerator Laboratory near Chicago Illinois. It operates at a center of mass energy of $\sqrt{s}$ = 1.96 TeV and is currently the highest energy hadron collider in the world. Two detectors, the Collider Detector at Fermilab (CDF) and D0, are operated at the Tevatron. During the period 1992 to 1996 known as Run I data was taken which led to many B physics measurements including the first measurement of $\sin(2\beta)$[2].

Since then the accelerator complex and the detectors have been upgraded to improve the luminosity and the physics reach with a large emphasis on heavy quark (c,b,t) physics. In March 2001 the Run II data taking began with the goal of collecting an integrated luminosity of 2 fb^{-1} over the next three years. This is 20 times the luminosity from Run I and coupled with improvements in the detectors will provide an increase in statistics of more than a factor of 40. In the period since the start of Run II the accelerator and detector upgrades have been debugging and commissioning. Since the start of 2002 physics results have started to become available.

2. b Quark Production at the Tevatron

The Tevatron is an excellent place to study B physics for several reasons.

- The large cross section ($\sim 100\mu b$) relative to $e^{+}e^{-}$ colliders (few nb).

- The production of a full spectrum of mesons and baryons with b quarks.

- Previous experience from Run I.

This gives access to a variety of B physics measurements[1]. Studies of the B_d^0 and B_s^0 systems give access to various CP parameters. Studies of rare decays give access to various CP effects as well as new physics. Measurements of the properties of the spectrum of B hadrons help constrain the Standard Model.

3. CP Violation Measurements

The 3×3 CKM matrix has three real parameters which conserve CP and one imaginary parameter which violates CP. The unitary nature of the matrix implies an orthogonality relation between the rows and columns. The presence of an imaginary parameter means that inner products of two rows or columns describe a triangle in the complex plane. CP violation in the B system is particularly interesting because the unitarity triangle defined by $V_{tb}^{*}V_{td} + V_{cb}^{*}V_{cd} + V_{ub}^{*}V_{ud} = 0$ has angles of the same order of magnitude. Results are then quoted as measurements of the angles of this triangle: $\alpha(\phi_2)$, $\beta(\phi_1)$, and $\gamma(\phi_3)$

CP violation can be studied in a variety of ways: direct CP violation in decay rates of particles and antiparticles, indirect CP violation in the mixing of neutral meson mass states, and interference between direct and indirect CP violation. One of the 'gold plated' modes of studying

CP violation uses mixing in the decay $B_d^0(\bar{B}_d^0) \to J/\psi K_s^0$ where the contributions from higher order penguins is negligible. Measurements of the time dependent and time integrated asymmetries between for this decay provide measurements of $\sin(2\beta)$ for the unitarity triangle as shown in equation 1.

$$\frac{N_{B_d \to J/\psi K_s^0} - N_{\bar{B}_d \to J/\psi K_s^0}}{N_{B_d \to J/\psi K_s^0} + N_{\bar{B}_d \to J/\psi K_s^0}} \propto \sin(2\beta)\sin(\Delta m_d t) \quad (1)$$

The statistical significance of this asymmetry is determined by ϵD^2 where ϵ is the efficiency of tagging (ϵ) and D is the asymmetry between wrong and right tags. Experimentally, the challenge is to maximize ϵD^2 through triggering and tagging algorithms.

During Run I the CDF collaboration was able to use its silicon vertex detector (D0 did not have a magnetic spectrometer during Run I) to perform a measurement of $\sin(2\beta)$[2] using the asymmetry in equation 1. A new Run I result[3] using the additional decay channel $B_d^0(\bar{B}_d^0) \to \psi(2S)K_s^0$ is given in equation 2 while the asymmetries are shown in figure 1.

$$\sin(2\beta) = 0.91 \pm 0.32(stat) \pm 0.18(syst) \quad (2)$$

This result is compatible with the latest results for $\sin(2\beta)$ from both Babar[4] and Belle[5].

Of particular interest for both CDF and D0 for Run II are measurements using $B_s^0(\bar{B}_s^0)$ mesons. Both experiments have set up detectors and triggers which are sensitive to both semileptonic and fully hadronic decay channels. The first measurement of interest is to observe B_s mixing by measuring the oscillation frequency $x_s = \Delta m_s/\Gamma$. This is analogous to the Δm_d term in equation 1. The difference is that $\Delta m_q \propto |V_{tb}^* V_{tq}|$ which implies that $\Delta m_s \gg \Delta m_d$ due to the fact that $|V_{ts}| \gg |V_{td}|$. To measure $B_s^0(\bar{B}_s^0)$ mixing therefore requires excellent ct resolution which will be available at the Tevatron through improved tracking and triggering systems and fully reconstructed hadronic final states at both CDF and D0.

Using combinations of the asymmetries for the decays $B_d^0(\bar{B}_d^0) \to \pi^+\pi^-$, $B_d^0(\bar{B}_d^0) \to \pi^+K^-$, and $B_s^0(\bar{B}_s^0) \to K^+K^-$ it is possible to get a handle on the values for the other two angles of the unitarity triangle: α and γ[6]. Preliminary results
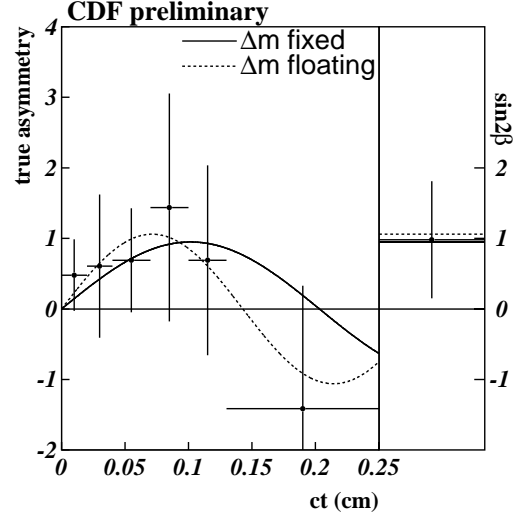

Figure 1. Latest $\sin(2\beta)$ measurement from CDF using the asymmetry in $B_d^0(\bar{B}_d^0) \to J/\psi K_s^0$ and $B_d^0(\bar{B}_d^0) \to \psi(2S)K_s^0$. The points with the curves are measurements of the time dependent asymmetry, while the single point on the right is the time integrated asymmetry.

for measurements of the first of these decays has already been presented by Babar and Belle, but by itself it suffers from significant theoretical uncertainties when used to extract a value for α or γ. Combinations of the first two decays reduce these uncertainties, but the cleanest method from a theoretical point of view uses a combination of the $B_d^0(\bar{B}_d^0) \to \pi^+\pi^-$ and $B_s^0(\bar{B}_s^0) \to K^+K^-$ decay asymmetries. Together the time dependent asymmetries for these two decays provide two measurements which can be interpreted in terms of two unknowns: β and γ. Using other measurements to constrain β allows one to overconstrain the unitarity triangle. Since measurements of the $B_s^0 \to K^+K^-$ asymmetry are not available at the B factories, this is an important channel where the Tevatron can contribute to the understanding of the parameters of the unitarity triangle. Figure 2 shows a preliminary result for $B_{d,u,s}$ decay to two hadrons using the partially commissioned
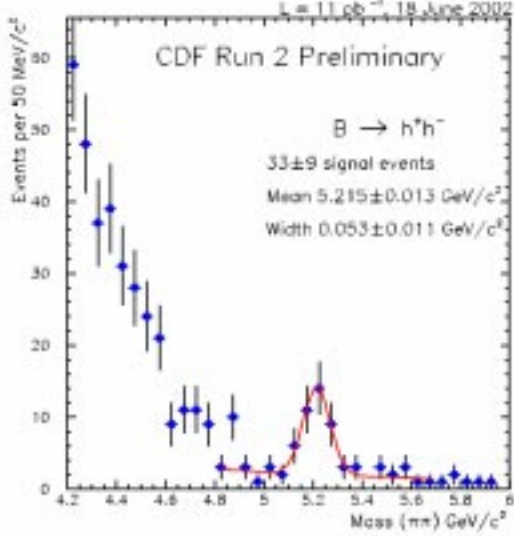
Figure 2. Preliminary result for $B_{d,u,s}$ decay to two hadrons from CDF. Both the silicon system and the displaced vertex trigger were still being commissioned.

Figure 3. Observation of $B_c^+ \to J/\psi \bar{l} \nu$ during Run I.

displaced vertex trigger at CDF.

4. Heavy Quark Spectroscopy

Many of the properties of the heavier B hadrons such as the B_s^0, B_c^+, and Λ_b^0 are either unmeasured or poorly measured. Since all species of B mesons and the lightest B baryons are produced at the Tevatron, a large number of B hadron spectroscopy experiments are planned for Run II. In fact, due to lower p_T thresholds, the same triggers used to enhance the bottom signal also yield a large number of reconstructed charm particles. During Run I the B_c was first observed at the Tevatron using the semileptonic channel[7] $B_c^+ \to J/\psi \bar{l} \nu$ as shown in figure 3 which allowed measurements of the mass and lifetime. Run I results for masses and lifetimes for B_s^0, B_c^+, and Λ_b^0 are summarized in table 1. During Run II other decay modes will provide new measurements of masses, lifetimes, and branching ratios. In addition to improved statistics for the B_c^+ semilep-
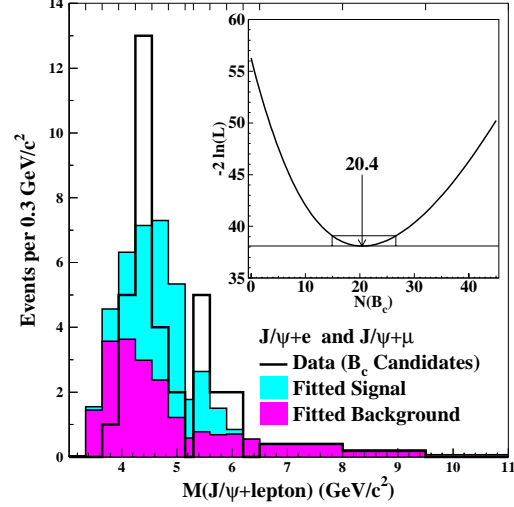
tonic decay, several fully hadronic modes will also be measured.

5. Cross Section for b Production

As shown in figure 4 the measured inclusive cross section [8,9] from Run I for $p\bar{p} \to b + X$ is a factor of ~ 2 higher than the value predicted by theory. Although new measurements will be done during Run II, the primary emphasis at the moment is on understanding the theory, which may lead to suggestions for new measurements.

6. Accelerator Upgrades

For Run II the accelerator complex at Fermilab was expanded and upgraded. The Main Injector was added as a replacement for the old Main Ring. This increased the proton luminosity available for Tevatron collider operations and antiproton production. Another advantage is that the Main Injector is located outside the Tevatron whereas the old Main Ring shared the same tunnel as the Tevatron which could lead to opera-

Table 1
Summary of Run I mass and lifetime measurements for B_s^0, B_c^+, and Λ_b^0.

	Mass (GeV/c^2)	Lifetime (ps)
B_s^0	$5.3699 \pm 0.0023 \pm 0.0013$	1.36 ± 0.10
B_c^+	$6.40 \pm 0.39 \pm 0.13$	0.46 ± 0.17
Λ_b^0	$5.621 \pm 0.004 \pm 0.003$	1.32 ± 0.17
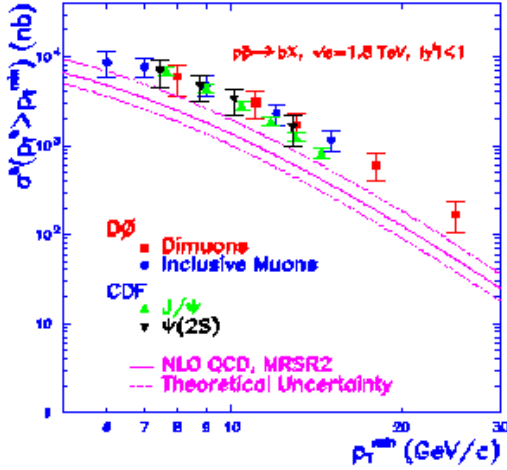
Figure 4. Inclusive b quark cross section from Run I showing discrepancy between measurement and theory.

7. Detector Upgrades

In order to pursue the previously described physics agenda the detectors at the Tevatron, CDF and D0, underwent extensive upgrades during the period 1996-2001. For the B physics programs at the two experiments, the upgrades needed to address the following needs.

- Excellent tracking and vertexing.

- Ability to trigger on displace vertices.

- Particle ID for flavor tagging.

- Excellent muon reconstruction.

- Well understood simulation.

- Efficient use of trigger bandwidth.

The upgraded CDF and D0 detectors are shown in figures 5 and 6.

At CDF these needs were addressed through a variety of upgrades which built on the extensive experience from Run I. The entire tracking volume was replaced with a faster and higher resolution silicon system surrounded by a fast gaseous tracking system. In addition to speed and resolution, the new silicon system covers a larger kinematic range with more redundancy. To handle the higher luminosities for Run II the entire data acquisition system was replaced with faster electronics. A displaced vertex trigger was added to the trigger, and a time of flight system was added just outside the tracking volume to extend the particle ID capabilities. Further details can be found in [10].

At D0 efforts were put into expanding on existing strengths in muon and reconstruction and calorimetry from Run I. The primary upgrade

tional problems. Improvements were also made directly to the $\bar{p}$ storage system to increase the rate of $\bar{p}$ accumulation. In order to handle the increased number of protons and antiprotons, the bunch structure in the Tevatron was changed. The first part of this change was to increase the bunches while decreasing the bunch spacing from 3.5 μs to 396 ns. This also helps reduce the event pileup at the detectors. All of these changes are focussed toward the goal of increasing the luminosity from a peak Run I luminosity of 2×10^{31} $cm^{-2}s^{-1}$ to 2×10^{32} $cm^{-2}s^{-1}$ by the end of Run II.
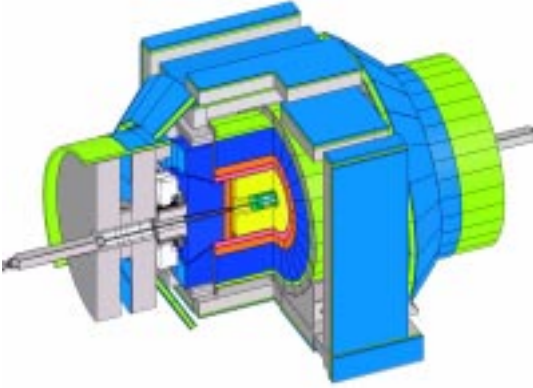
Figure 5. Cutaway view of the CDF Run II detector. Colors indicate the various components: tracking (green, orange), calorimetry (red, dark blue) and muons (yellow, turquoise).
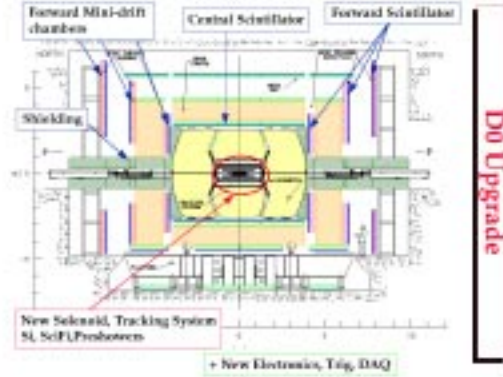

Figure 6. Side view of the D0 Run II detector. Colors indicate various components: tracking (red circle), calorimetry (yellow), and muons (blue, orange, green).

which affected the B physics program was the installation of a magnetic spectrometer inside the calorimeter. Inside the magnet is a tracking volume composed of a silicon system surround by a fiber tracker. Similar to CDF, the entire data acquisition system was replaced with faster electronics. A displaced vertex trigger was also added to the trigger. Further details can be found in [11].

8. Status and Plans

The B physics program at the Tevatron for Run II will go through various stages. In the first 50 pb^{-1} (about halfway there at this point) we will be refining triggers and performing various high rate measurements. In the second stage (50-200 pb^{-1}) we plan to have our first Run II $\sin(2\beta)$ result along with a measurement of B_s^0 mixing. In the third stage (200+ pb^{-1}) we will be refining measurements from the first two stages with higher statistics as well as looking for rare decays, etc. Throughout these periods we will be measuring a variety of lifetimes, cross sections, and branching ratios. In conclusion, there are many new an interesting B physics results which will come out of Run II at the Tevatron which both complement and extend the programs at the B factories.

REFERENCES

1. K. Anikeev, *et. al.*, FERMILAB-Pub-01/197 (2001).
2. F. Abe, *et. al.*, The CDF Collaboration, Phys Rev Lett **81** 5513 (1998).
3. http://www-cdf.fnal.gov/physics/new/bottom/ sin2beta/sin2beta.html.
4. B. Aubert, *et. al.*, The Babar Collaboration, submitted to Phys Rev Lett.
5. K. Abe, *et. al.*, The Belle Collaboration, submitted to Phys Rev D.
6. Fleischer, Phys Lett **B459** 306 (1999).
7. F. Abe, *et. al.*, The CDF Collaboration, Phys Rev Lett **81** 2432 (1998).
8. F. Abe, *et. al.*, The CDF Collaboration, Phys Rev **D50** 4252 (1994).
9. S. Abachi, *et. al.*, The D0 Collaboration, Phys Rev Lett **74** 3548 (1995).
10. S. Miller, these proceedings.
11. R. Jesik, these proceedings.